A LONGITUDINAL STUDY OF DENTINE LEAD LEVELS, INTELLIGENCE, SCHOOL PERFORMANCE AND BEHAVIOUR

PART III. DENTINE LEAD LEVELS AND ATTENTION/ACTIVITY

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Abstract—The relationship between dentine lead levels and maternal/teacher ratings of inattentive/restless behaviour in children was examined for a birth cohort of New Zealand children. There were small but relatively consistent and stable correlations between dentine lead values and behaviour ratings. After correction for errors of measurement in dentine lead values and behaviour ratings it was estimated that the correlation between lead levels and inattentive/ restless behaviour was in the region of + 0.18. However, after control for various sources of confounding there was only a small, but statistically significant, correlation of + 0.08 between lead levels and inattention/restlessness in children. It is concluded that the weight of the evidence favours the view that there is a very weak causal association between lead levels and attention and activity levels in children.

Keywords: Longitudinal study, dentine lead, child behaviour, hyperactivity

INTRODUCTION

In a previous paper we examined the relationship between dentine lead levels and measures of cognitive ability in a birth cohort of New Zealand children studied until the age of nine years (Fergusson, Fergusson, Horwood & Kinzett, 1988). This analysis suggested the presence of small consistent associations between dentine lead levels and all measures of school performance. Measures of intelligence were, however, unrelated to dentine lead when confounding factors were taken into account. It was suggested that the relationship between school performance and dentine lead levels could have arisen because lead exposure may lead to deficits in attentional processes which in turn impair long term school achievement. This paper examines the relationship between dentine lead levels and measures of inattentive, restless behaviour in the birth cohort of children examined in the earlier paper. The background to this research is developed below.

A number of studies have examined the relationship between behaviour in children and lead levels. These studies have produced inconsistent and inconclusive results, with some studies suggesting linkages between behaviour measures and lead levels (David, Clark & Voeller, 1972; David, Hoffman, McCann, Sverd & Clark, 1976; David, Hoffman, Clark, Grad & Sverd, 1983; De la Burde & Choate, 1972; Needleman, Gunnoe, Leviton, Reed, Peresie, Maher & Barrett, 1979; Silva, Hughes, Williams & Faed, 1985; Yule, Lansdown, Hunter, Urbanowicz, Clayton & Delves, 1983) and other studies failing to find evidence for such an association (Albert, Shore, Sayers, Strehlow, Kneip, Pasternak, Freidhoff, Coran & Crinono, 1974; Baloh, Strum, Green & Gleser, 1975; Lansdown, Shepherd, Clayton, Delves, Graham & Turner, 1974; McNeil, Ptasrik & Croft, 1975; Ratcliffe, 1977; Rummo, Routh, Rummo & Brown, 1979; Smith, Delves, Lansdown, Clayton & Graham, 1983). In a recent review of this evidence Lansdown (1986) concluded '. . . the most recent epidemiological studies have failed to produce convincing *consistent* evidence for an association between moderate levels of lead and behavioural patterns in general; even less is the evidence on lead and hyperactivity' (p. 267).

These findings are highly reminiscent of the findings for lead and cognitive ability where similar inconsistent and confused results have emerged. In common with studies of cognitive ability, studies of lead and behaviour are subject to a number of recurrent methodological criticisms. These criticisms have been reviewed elsewhere (Bornschein, Pearson & Reiter, 1980; Harvey, 1984; Fergusson *et al.*, 1988; Rutter, 1980; Smith, 1985) and include: inadequate measurement of lead burden; problems of validity and reliability with tests; inadequate control of confounding covariates; problems of statistical power; lack of comparability between studies and sample selection biases. Of these criticisms, issues relating to the reliability and validity of tests are likely to be the most important for measures of child behaviour. In nearly all studies, measures of behaviour have been based on ratings of the child made by parents or class teachers. However, it is well known that parent and teacher ratings of children are only modestly correlated (e.g. Peterson, Becker, Shoemaker, Luria & Hellmer, 1961; Rutter, Tizard & Whitmore, 1970). This result raises issues about the convergent validity of these measures. In particular, it seems likely that ratings of children may reflect the effects of three quite different sources of variation:

    (i) variation due to random errors of measurement;
    (ii) variation due to method or situation specific factors;
    (iii) variation due to the child's generalized behavioural tendencies.

The relatively small correlations between maternal and teacher ratings of children tend to suggest that a large proportion of the variance in these ratings can be attributed to either random errors of measurement or method/situation specific factors. A recent analysis of this issue by Fergusson and Horwood (1987a) suggests that in the region of one third of the variance in behaviour ratings reflects the child's generalized behavioural tendencies and the remaining variance can be attributed to method effects or random errors of measurement. The effects of this variance may be to depress substantially the correlations between behaviour measures and other variables (Fergusson & Horwood, 1987b). This seems likely to happen in analyses of lead and behaviour ratings since one would expect that lead values would be uncorrelated with random errors of measurement and method specific effects but may be correlated with the child's generalized behavioural tendencies.

In this paper we report on a study of the relationship between lead and attentional processes in children. This study is characterized by the following features:

(1) it is based on a relatively large ($N = 888$) sample of children;
(2) data on behaviour have been collected longitudinally over a 1 yr period;
(3) the analysis incorporates procedures for estimating the magnitude of random errors of measurement and method effects in behavioural ratings;
(4) the associations between dentine lead values and measures of behaviour are corrected for the effects of an extensive set of prospectively collected covariates; and
(5) procedures for estimating the effects of sample selection factors are incorporated into the analysis.

In general terms, the aims of the research are to determine whether dentine lead levels and measures of attention are associated when various sources of confounding, including errors of measurement in behaviour ratings, confounding covariates and sample selection biases, are estimated.

METHOD

The data were collected during the first 11 stages of the Christchurch Child Development Study. In this study a birth cohort of children born in the Christchurch (New Zealand) urban region during mid 1977 has been studied at birth, 4 mths and annual intervals until the age of 9 yrs. The data used in this analysis were collected in the following ways.

(1) Dentine Lead: During the course of the study, children participating in the research were asked to supply shed deciduous teeth. Teeth were analysed using methods similar to those employed by Needleman *et al.* (1979). These methods have been described in detail in a previous paper (Fergusson, Fergusson, Horwood and Kinzett, 1987). For each child, two estimates of dentine lead were available for separate samples (chips) of dentine. In this analysis these measures were used in two ways: (i) in the analysis of bivariate associations between dentine lead and behaviour ratings (Table 1) the average of the chip values was used to estimate dentine lead values; (ii) in subsequent analyses the separate chip values of the dentine lead samples were used as multiple indicator variables of the child's true but non-observed level of dentine lead. In all analyses dentine lead values have been transformed to log units since these values approximated a log normal distribution (Fergusson *et al.*, 1987).

(2) Measures of Behaviour: When children were aged 8 and 9 yrs the child's mother and class teacher completed an extensive behaviour rating instrument based on a combined measure using the Rutter (Rutter *et al.*, 1970) and Conners (Conners, 1969, 1970) behaviour rating questionnaires. All items were scored using the three point scoring method devised for the Rutter scales. In this analysis, concern is restricted to a subset of the items in these tests. These items are test items which measure either inattention or restless, active behaviour in the child. There was a total of eight items from maternal ratings and eight items from teacher ratings. These items are shown in Table 1. To measure overall trends in maternal and teacher ratings, the ratings were summed to produce an overall score for each measurement source (mother/teacher) at each year. The use of an item sum was justified on the grounds that analyses of maternal and teacher ratings showed that these ratings were adequately described by a single factor model.

(3) Covariates: From the data collected during the course of the Study the following covariates were available to adjust correlations between dentine lead and behaviour ratings.
   (i) Measures of maternal and paternal education levels.
   (ii) Measures of family socio-economic standards including: family income; family living standards; family socio-economic status; child's ethnicity; the child's family placement at birth.
   (iii) Family social environment: The planning of pregnancy; the duration of time for which the child was breast fed; age at which the child was introduced to solid feeding; maternal smoking habits; measures of mother–child interaction based on the avoidance of punishment and

restriction and the maternal emotional responsiveness subscales of the HOME inventory (Elardo, Bradley & Caldwell, 1977); residential stability; the number of changes of parent figures the child had experienced from birth to 8 yrs; the number of adverse life events reported by the family from 1 to 8 yrs.

(iv) Child's perinatal history: Birthweight, gestational age and birth order.

(v) Child's school experiences: The number of years for which the child had attended preschool; number of changes of school.

(vi) Factors related to lead exposure: number of old (40 yrs +) weatherboard houses that the child have lived in; the number of years for which the child had lived on roads with a traffic density in excess of 5000 vehicles per day; pica during childhood.

(vii) Factors relating to sampling of teeth; age at which tooth was shed; the position of the shed deciduous tooth.

(A more detailed account of these covariates is available from the authors).

Sample sizes and sample selection hazards

The original cohort on which this study was based comprised 1265 children. However, in the analyses reported here, sample sizes are substantially smaller than this. The analysis is based on the sample of children for whom complete data on dentine lead values, behaviour at 8 and 9 yrs and all covariates were available. This sample comprised 888 children who represented 70% of the original cohort and 82% of all children studied at age 9 yrs. Sample attrition arose from two major sources. First, over the duration of the study, a number of children were lost to follow up and by 9 yrs the number of children studied had reduced to 1079 children, who represented 85% of the original cohort. In addition some children failed to supply shed deciduous teeth—of the children studied to age 9 yrs, useable teeth were available for only about 90% of this group.

The relatively large sample attrition raises the possibility that sample losses may have been non-random, leading to possible sample selection bias. To correct for the effects of possible bias, the method described by Berk (1983) was used. This method involves two stages of analysis. In the first stage a sample selection equation is estimated. This estimates a hazard statistic which describes the probability that a subject with a given set of characteristics will be excluded from the sample under study. In the second stage of the analysis the estimated hazard statistic is introduced into substantive regression equations to compensate for sample selection effects. This method was applied to the present data as follows. From information collected at the child's birth it was possible to estimate the probability of the child being included in the sample analysed, conditional on the child's social and related characteristics at birth. This analysis suggested the presence of small and diffuse tendencies for children who were disadvantaged at birth to be under-represented in the sample. These tendencies arose predominantly because disadvantaged children were less likely to supply shed deciduous teeth. To adjust for sample selection bias a logistic regression equation was solved in which the probability of being excluded from the sample of 888 children was regressed on measures of the child's social and other characteristics at birth. Significant sample selection factors were the child's birth weight, maternal smoking during pregnancy and maternal age. The estimated hazard was simply the probability estimated from the regression model that a child with given characteristics at birth would be excluded from the sample of 888 children.

RESULTS

(a) *Bivariate correlations between behaviour ratings and dentine lead values*

Table 1 shows the product–moment correlations between dentine lead values (measured in log units) and maternal and teacher ratings of various aspects of the child's attention and activity levels. These tables suggest the following conclusions:

(1) For maternal ratings, there are small and diffuse correlations between dentine lead values and measures of activity and attention. These correlations are generally statistically significant and ranged from 0.03 to 0.09. The general trends in the data

are reflected in the total item scores which were correlated $+0.11$ with lead values at age 8 yrs and $+0.08$ at 9 yrs.

(2) For teacher ratings of behaviour, similar results were obtained. However, the correlations between lead values and teacher ratings appear to be slightly larger than for maternal ratings. These correlations range from 0.03 to 0.16. The general trends in the teacher ratings are reflected by the correlations between the items sums and dentine lead values. At 8 yrs this correlation was $+0.13$ and at 9 yrs $+0.14$.

The general impression conveyed by Table 1 is of the presence of small, consistent and relatively stable correlations between dentine lead values and ratings of over-active or inattentive behaviour in children.

TABLE 1. PRODUCT MOMENT CORRELATIONS BETWEEN MATERNAL, TEACHER BEHAVIOUR RATINGS AND DENTINE LEAD VALUES ($\log \mu g\ c^{-1}$)

	8 yrs		9 yrs	
	r	p^*	r	p^*
Maternal ratings				
Activity				
Restless, overactive	0.07	< 0.05	0.05	< 0.10
Excitable, impulsive	0.07	< 0.05	0.05	< 0.10
Constantly fidgeting	0.03	N.S.	0.04	N.S.
Always climbing	0.07	< 0.05	0.04	N.S.
Squirmy, fidgety	0.03	N.S.	0.06	< 0.05
Attention				
Short attention span	0.09	< 0.01	0.08	< 0.01
Inattentive, easily distracted	0.09	< 0.01	0.05	< 0.10
Can't settle to tasks	0.06	< 0.05	0.04	N.S.
Total score	0.11	< 0.01	0.08	< 0.05
Teacher ratings				
Activity				
Restless, overactive	0.09	< 0.01	0.11	< 0.001
Excitable, impulsive	0.03	N.S.	0.10	< 0.001
Squirmy, fidgety	0.11	< 0.001	0.13	< 0.001
Very restless	0.10	< 0.001	0.13	< 0.001
Attention				
Inattentive, easily distracted	0.16	< 0.001	0.14	< 0.001
Short attention span	0.11	< 0.001	0.12	< 0.001
Poor concentration	0.13	< 0.001	0.12	< 0.001
Total Score	0.13	< 0.001	0.14	< 0.001

*One-tailed test

(b) *Correction for errors of measurement in ratings*

The correlations in Table 1 are likely to underestimate the true correlations between dentine lead levels and behavioural tendencies since the behaviour ratings are likely to contain sources of error variance which depress these correlations. As discussed in a previous paper (Fergusson & Horwood, 1987a) these sources of error variation are likely to arise from both random errors of measurement and the presence of method
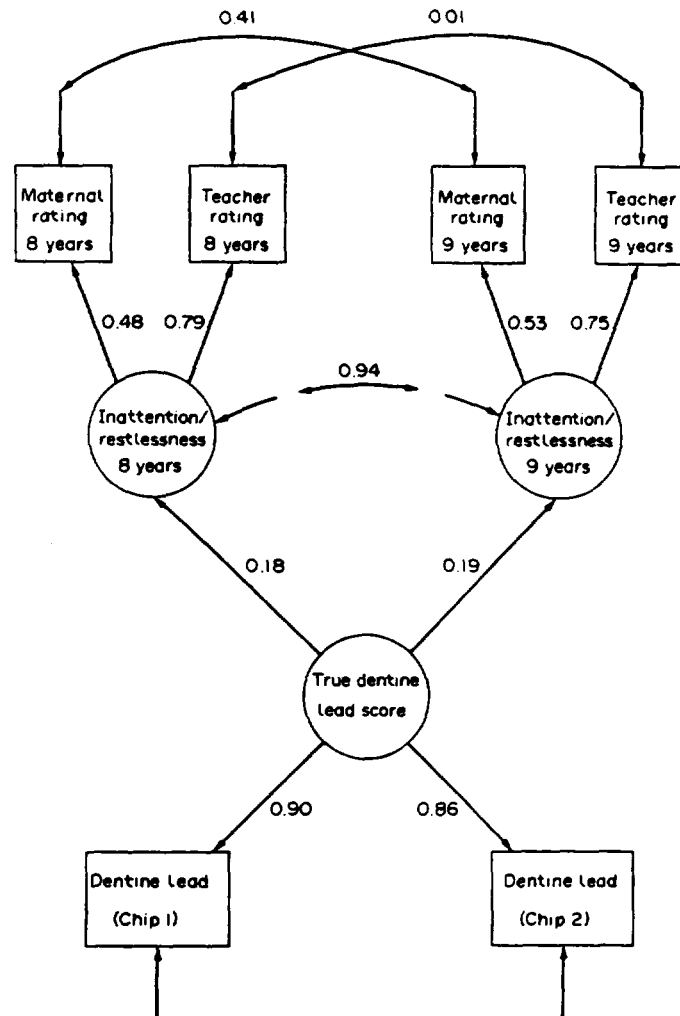
Fɪɢ. 1. Model of dentine lead values and maternal and teacher ratings of behaviour. (All coefficients are standardized.)

or situation specific variance in behaviour ratings. To deal with this problem the model depicted in Fig. 1 was fitted to the matrix of intercorrelations between dentine lead chip values and maternal and teacher ratings of behaviour (Table 2). This model assumes the following:
(1) at each year, maternal and teacher ratings are assumed to be fallible indicator measures of underlying dimensions of inattention/restless behaviour in the child. This aspect of the model assumes that the observed variance in behaviour ratings is attributable to variance arising from the non-observed constructs and a

TABLE 2. MATRIX OF CORRELATIONS BETWEEN DENTINE LEAD VALUES $(\log \mu g\ g^{-1})$ AND MATERNAL, TEACHER BEHAVIOUR SCORES

	Chip 1	Chip 2	M8	T8	M9	T9
Lead chip 1	1					
Lead chip 2	0.78	1				
Maternal 8 years (M8)	0.09	0.10	1			
Teacher 8 yrs (T8)	0.12	0.13	0.38	1		
Maternal 9 yrs (M9)	0.06	0.07	0.65	0.38	1	
Teacher 9 yrs (T9)	0.13	0.14	0.38	0.57	0.39	1
Standard deviation	0.54	0.55	3.24	3.32	2.81	3.41

disturbance variable reflecting both random errors of measurement and method specific components of the ratings;

(2) the disturbance terms of measures derived from the same source (i.e. mother/teacher) but at different times are permitted to be correlated, reflecting the presence of common method variance in these disturbances;

(3) dentine lead values are assumed to exert a direct casual effect on behaviour ratings at each measurement period; and

(4) dentine lead values are measured by a true score model (Fergusson *et al.*, 1987) which assumes that the variance in the observed dentine lead values is attributable to underlying true dentine lead values and random errors of measurement.

This model is one of the class of covariance structure models which may be fitted by the LISREL programme (Joreskog & Sorbom, 1984). The model can be shown to be identified, and the identification status of the model is very similar to that of the well known model presented by Wheaton, Muthen, Alwin and Summers (1977). In solving this model it was found that a number of equality constraints could be imposed on model parameters without significantly influencing model fit. These constraints were that: the coefficients from maternal ratings to the constructs were equal at 8 and 9 yrs; the coefficients from teacher ratings to the constructs were equal at 8 and 9 yrs; and that lead was assumed to have an identical causal effect at 8 and 9 yrs. These restrictions were imposed on the model since such over-identifying conditions typically result in an increase in the precision of estimators (Kenny, 1979). The coefficients in the model in Fig. 1 are estimates of the standardized model coefficients derived from the data in Table 2. These coefficients do not satisfy exactly the equality constraints noted above since the model was solved using the unstandardized variance/covariance matrix and this does not imply corresponding equality of standardized parameters. The standardized parameters may be interpreted in a way which is analogous to standardized regression coefficients or factor loadings. The fitted model leads to the following conclusions.

(1) The coefficients linking and teacher ratings to the underlying constructs of inattention/restlessness are estimates of the direct correlations between these ratings and the underlying constructs. For maternal ratings these coefficients are in the region of 0.50 and for teacher ratings in the region of 0.77. The result implies that teacher ratings were a more accurate measure of child behaviour. This might be expected since teachers typically will be more affected by inattentive/restless behaviour.

(2) The coefficients linking the dentine lead values to the underlying constructs are estimates of the effects of lead on behaviour under the assumptions of the model. They are also the correlations between dentine lead levels and the constructs. These coefficients are in the region of + 0.18, suggesting the presence of a modest tendency for inattentive, restless behaviour to increase with increasing dentine lead values. It will be noted that the estimated correlation of + 0.18 is substantially higher than the estimates in Table 1. This arises because the fitted model takes account of fallibility in both the measurement of lead and the measurement of behaviour.

(c) *Correction for confounding covariates*

The model in Fig. 1 permits the estimation of the correlations between dentine lead values and behaviour ratings corrected for errors of measurement. However, this model does not include any correction for confounding covariates which might influence lead values and behaviour scores giving rise to spurious correlations. To deal with this issue the model in Fig. 2 was fitted to the data. This model is similar to the model in Fig. 1 but includes the potential for confounding covariates to influence lead and behaviour scores. This model was solved using the covariates described in the Method section and also included the sample selection hazard as a regressor variable to compensate for non-random sampling. The results of this analysis are summarized in Table 3, which gives estimates of standardized regression coefficients for the three regression equations implied by Fig. 2. These equations are: (i) the regression of lead on the covariates; (ii) the regression of 8 yr behaviour scores on lead and the covariates; (iii) the regression of 9 yr behaviour measures on lead and the covariates. These regression equations included all covariates which were significantly related to either lead values or behaviour measures.
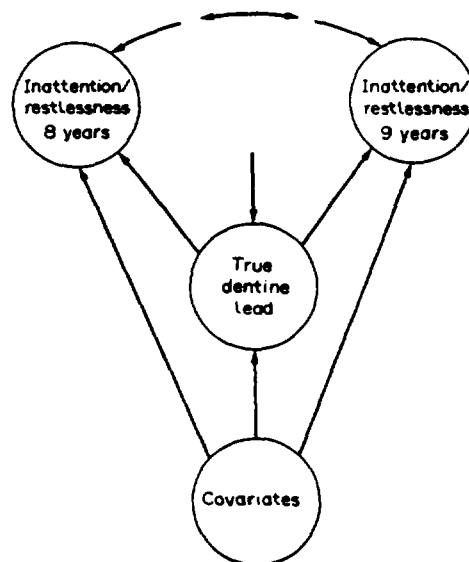

Fig. 2. Model of covariates, dentine lead values and inattentive/restless behaviour.

The table shows that after adjustment for covariates and sample selection hazards, the standardized regression coefficients between lead and inattention/restlessness are in the region of +0.10. While this is substantial reduction on the standardized coefficient of +0.18 estimated in the model in Fig. 1, the association between lead and inattention/restlessness remains statistically significant $(P < 0.01)$. It may be concluded that after control for confounding covariates and sample selection hazards, there is still a small tendency for increasing dentine lead values to be associated with increases in inattentive or restless behaviour in children.

TABLE 3. SUMMARY OF COVARIATE ADJUSTMENT EQUATIONS (ALL COEFFICIENTS ARE STANDARDIZED)

| | | Dependent variable | |
Predictor	Lead	Inattention/ restlessness 8 yrs	Inattention/ restlessness 9 yrs
Lead	•	0.10	0.10
Covariates			
Maternal education	—	-0.12	-0.12
Birth placement	0.07	—	—
Child's gender	—	-0.32	-0.34
Standard of living	0.17	0.08	0.08
Avoidance of punishment	—	0.21	0.22
Change of parents	—	0.09	0.09
Changes of school	—	0.11	0.11
Old weatherboard houses	0.13	—	—
Traffic density	0.07	—	—
Age of tooth	0.06	—	—
Tooth position	0.10	—	—
Sample selection hazard	0.17	0.07	0.07
Multiple correlation	0.38	0.53	0.56

(d) *Pica and reverse causality*

The covariates in the analysis in Table 3 do not include pica. The reason for this can be seen from Fig. 3a. This figure shows the theoretical relationships which are assumed to exist between lead levels, behaviour, the covariates and pica. It may be seen that while the covariates exert a common effect on both lead and behaviour, the relationships between dentine lead values, pica and behaviour are more complex: lead is assumed to influence behaviour; pica is assumed to be influenced by behaviour; and pica is assumed to influence lead. This pattern of cyclic relationships cannot be estimated by introducing pica as a covariate.

Ideally one would solve the model in Fig. 3a but in practice this is not possible since there is not sufficient information available to identify this model. However, the weaker model in Fig. 3b can be solved. This model deletes the path between lead and behaviour and thus assumes that all of the correlation between lead and behaviour is explained by the common effects of the covariates or by reverse causality mediated by pica. If this model fits the data it can be concluded that the apparent correlations between lead and behaviour can be adequately explained by the confounding effects of the covariates and reverse causality. If this model does not explain this correlation
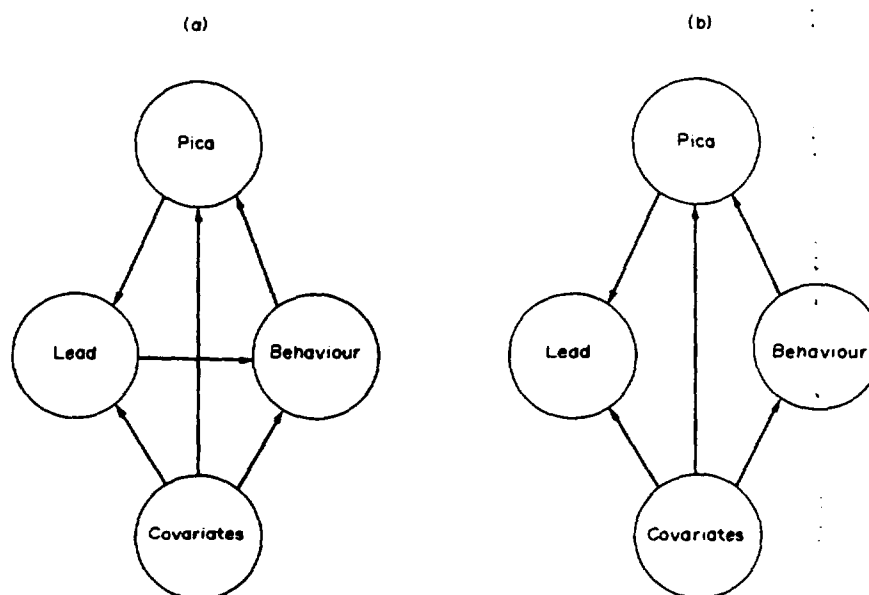
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(a)   (b)

Fɪɢ. 3. Theoretical models of lead, behaviour, pica and covariates. (For simplicity only one time period is shown.)

then the evidence suggests (but does not establish) a direct causal effect of lead on behaviour. This model was fitted to the data using LISREL methods (details of the model specification are available from the authors). The results of the analysis are summarized in Table 4. This table shows the estimated correlation between dentine lead values and inattentive/restless behaviour partitioned into two components:

(i) a component attributable to the net effects of all sources of confounding including the covariates, sample selection hazards and reverse causality; and
(ii) the residual unexplained correlation.

This table suggests that when all sources of confounding had been estimated there was still a small but statistically significant ($P < 0.01$) correlation of $+0.08$ between lead and inattention/restlessness.

TABLE 4. CORRELATIONS BETWEEN TRUE DENTINE LEAD VALUES AND INATTENTIVE/RESTLESS BEHAVIOUR
BEFORE AND AFTER CONTROL FOR COVARIATES, PICA AND SAMPLE SELECTION FACTORS

	Estimated correlation	Correlation due to confounding factors	Unexplained correlation	P
8 yrs	0.18	0.10	0.08	< 0.01
9 yrs	0.19	0.11	0.08	< 0.01

DISCUSSION

In agreement with the general trends in some previous studies there was a small tendency for ratings of inattentive, restless behaviour in children to be related to dentine lead values. The observed correlations for maternal and teacher ratings were in the region of +0.08 to +0.14, suggesting the presence of a weak tendency for increasing dentine lead to be associated with increasing inattentive and restless behaviour. However, the observed correlations appeared to substantially under-estimate the true associations between dentine lead values and inattentive/restless behaviour in children. Correction for errors of measurement in behaviour ratings and dentine lead values suggested that this correlation was in the region of +0.18. This finding may explain some of the instability that has been found in studies of behaviour ratings, since the presence of errors of measurement in behaviour ratings may introduce substantial sources of imprecision into analyses and impart a marked downward bias to correlations. This effect of errors of measurement in behaviour ratings has been noted in a previous paper (Fergusson & Horwood, 1987b). When the downward bias caused by measurement error is coupled with the relatively small samples used in many previous studies it is hardly surprising to find that correlations between lead and inattentive/restless behaviour have been small and inconsistent.

After control for various sources of confounding including covariates, sample selection effects and reverse causality via pica, the unexplained correlation between lead and inattention/restlessness was found to be +0.08. This suggests that a substantial component of the bivariate correlation between these variables was spurious and arose from confounding effects. Nonetheless, the residual correlation of 0.08 was statistically significant, suggesting the presence of a very small tendency for lead and inattentive/restless behaviour to be associated even after control for confounding. This small residual correlation may reflect a cause and effect association whereby low level lead exposure acts to influence attention and activity levels in children.

In favour of a causal interpretation the following points may be made.

1. The interpretation is biologically plausible since lead is a known neurotoxin which has disruptive effects on behaviour and cognitive ability at higher dosages. It is reasonable to assume that at low doses some residual effect of this toxicity may be present. This view is reinforced by the results of in vivo (Silbergeld, 1983) and in vitro (Otto, Benignus, Muller & Barton, 1983) studies which have suggested that lead exposure has continuous dose/response effects.

2. The evidence is very broadly consistent with previous studies which have at least hinted at the fact that the low level lead exposure may disrupt attentional processes. Perhaps the most compelling evidence is that provided by the chelation studies reported by David et al. (1983) which have suggested that lead exposure has reversible effects on hyperactive behaviour. While this evidence is controversial (Rutter, 1983; Lansdown, 1986) it is, at least, consistent with the results reported here.

3. The correlation persisted after extensive control for various sources of confounding including the effects of covariates, sample selection factors and pica.

4. The relationships between lead and behaviour were found to be stable over a 1 yr period. This reduces the likelihood that the correlations between lead and behaviour were the result of type I statistical errors.

5. The fact that dentine lead levels are likely to be fallible measures of the child's neurological exposure to lead tends to strengthen a causal interpretation since one might expect this fallibility to result in conservative estimates of the relationship between lead levels and behaviour.

6. In comparison to other studies, lead levels for this sample were low (Fergusson *et al.*, 1988). This restricted range of lead values is likely to reduce correlations between lead and behaviour, implying that stronger associations between lead and behaviour may be present in populations with a wider range of lead values.

Against a causal interpretation the following points may be made.

1. The unexplained correlation between lead and behaviour after adjustment for sources of confounding is small. This implies that further control of this association could easily reduce it to the point of statistical and practical insignificance.

2. The possibility remains that the analysis excluded some critical covariate(s) which lead to spurious associations between lead and behaviour.

3. While it has been possible to control errors of measurement in lead and behaviour measures, similar control for errors of measurement in the covariates was not possible. It is possible that such errors could have led to the covariates undercontrolling the associations between lead and behaviour.

4. Perhaps the most serious problem concerns the possibility that lead and behaviour are related by a reverse causality model in which variations in child behaviour lead to variations in lead burden. It is possible, for example, that children who are restless and inattentive may act in certain ways which increase body lead burden. While some attempt has been made to control for reverse causality via pica the possibility remains that there are other uncontrolled paths by which variations in behaviour lead to variations in lead levels. This is an extremely difficult hypothesis to examine since to adequately test a reverse causality model would require extensive longitudinal data on both lead and behaviour patterns to determine the relationships between growth in lead values and changes in behaviour patterns.

The analysis is based on a linear covariance structure model and this raises the issue of the appropriateness of using product–moment correlations to analyse the data. In particular, the distributions of the behaviour ratings showed a marked positive skew, violating the assumption of multivariate normality that underlies the maximum likelihood estimation. However, recent evidence (e.g. Huba & Harlow, 1987) suggests that these methods are robust to violations from normality. In addition, in an empirical analysis of similar data, Fergusson and Horwood (in press) have shown that very similar results are obtained using a variety of estimation methods including maximum likelihood estimation, polychoric correlations and transformations of the scale of measurement.

While the interpretation of the small correlation between lead levels and restless/inattentive behaviour in children is equivocal, we are inclined to the opinion that the weight of the evidence suggests the presence of a very small causal association by which increases in lead values are associated with increases in rates of inattentive/restless behaviour. At the same time, these findings could be explained by a reverse causality model in which inattention is symptomatic of general behavioural trends in children which give rise to variations in lead levels.

While the weight of the evidence from this analysis favours the view that low levels

of lead exposure may impair attentional and related processes in children, we do not believe that this evidence provides a justification for the view that the reduction of environmental lead levels will make a major contribution to the wellbeing of children. The estimated correlations are small and their interpretation is equivocal. Under these circumstances the findings, at best, provide some limited support for the eminently sensible and cautious view that it is wisest to make all reasonable attempts to reduce all sources of environmental lead to a minimum.

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